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THE VISCOSITY OF OPTICAL GLASS

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ABSTRACT

This is a report of a laboratory investigation of the viscosities of six optical glasses at high temperatures. A modified Searle type of concentric cylinder viscometer was used. The method of calibrating the viscometer is described, including the determination of frictional and "end effect" corrections. The important factors and formulas involved in the computation of viscosities from experimental data are given. A graph is shown of the logarithms of the viscosity values for a given glass plotted against the corresponding temperatures. Equations are given expressing the mathematical relations of viscosity to temperature. Included is a brief discussion of the viscosity changes resulting from volatilization and pot dilution during measurement, and of the consequent difficulty in determining the exact composition at the moment measurement is made.

CONTENTS

		Page
I.	Introduction	65
II.	Choice of method	65
III.	Description of apparatus	66
	1. Furnace	66
	2. Cylinders (crucible and stirrer)	66
	3. Driving mechanism	66
	4. Timing equipment	67
	5. Temperature measuring equipment	68
IV.	Equation for viscosity	68
V.	Evaluation of corrections	68
	1. The attainment of constant speed	69
	2. Friction corrections	69
	3. Evaluation of "end effect"	70
	4. Relation of effective load to r.p.m	72
VI.	Method of procedure for measuring viscosity of glass	72
	1. Adjustment of set-up	72
	2. Determination of bottom clearance D and "wetted height," h	73
VII.	Glasses studied	74
VIII.	Results	74
IX.	Summary and conclusions	78

I. INTRODUCTION

In the manufacture of optical glasses a knowledge of the viscosity-temperature relations is helpful in determining the most desirable melting and fining temperatures and conditions for stirring. The purpose of this report is to record results obtained by the modification of, and application to six optical glasses, of one of the common methods of measuring viscosities at high temperatures.

II. CHOICE OF METHOD

A brief résumé of the various methods used by earlier investigators is given by Washburn.[1] A survey of these methods of measuring

[1] E. W. Washburn, G. R. Shelton, and E. E. Libman, The Viscosities and Surface Tensions of Soda-Lime Glasses, Eng. Exp. Sta., University of Illinois, Bulletin no. 140, 1924.

viscosities had led earlier Bureau of Standards investigators [2] to adopt Searle's [3] modification of Margules' [4] method as the one seemingly best adapted to meet the requirements. This method depends on the measurement of the torque required to rotate the inner of two concentric cylinders, the outer cylinder being fixed and the material under test being confined between the two cylinders.

III. DESCRIPTION OF APPARATUS

A lateral view of the complete set-up is shown in figure 1.

1. FURNACE

The furnace was of the electrical resistance type, heated by three elements of 80 percent platinum-20 percent rhodium wire. These elements were supported by two disks and a cylinder of bonded artificial corundum forming the top, bottom, and sides of the heating chamber which was 12 cm deep by 7.6 cm in diameter. The assembled furnace was thoroughly insulated as shown in figure 1.

2. CYLINDERS (CRUCIBLE AND STIRRER)

The stationary cylinders or crucibles (c) were 6.2 cm in internal diameter and 9.0 cm in height and were so mounted as to prevent rotation. The stirrers, or rotating cylinders (Q) were closed-end tubes about 23 cm long. The portion immersed in the glass was ground to a flat-bottomed cylinder of 1.7 ± 0.0025 cm external diameter.

3. DRIVING MECHANISM

The driving mechanism is shown in the upper portion of figure 1. The hollow stirrer shaft (s) which carried the stirrer clamp (E) was mounted on ball bearings (u, u) and was rotated by means of the drum (f) which was 5.08 cm in diameter. On this drum were wound two fine braided silk cords which passed over adjustable, ball-bearing pulleys (a, a) to the driving masses (m, m). To keep the total driving weight constant, other sections of the cord continued to the floor.

In order to maintain a constant linear relation of machine friction to total pan load, the ball bearings on which pulleys (a, a) rotated were "run in" at about 1,000 r.p.m. for 3 hours with emery flour and kerosene, thoroughly cleaned, and then lubricated by touching 2 or 3 balls of each bearing with the best porpoise oil obtainable. The moment of inertia of the rotating system was increased by mounting a metal disk (M) on the upper end of the shaft (s).

It was found necessary also to alter the face of each pulley so that the cord, instead of running in a V-groove, ran over a cylindrical pulley face. The driving mechanism with its mounting was made adjustable horizontally and vertically by screws (A) and (B).

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[2] L. A. Palmer, E. J. TePas, W. Scholl, and G. L. Bixby.

[3] G. F. G. Searle, A Simple Viscometer for Very Viscous Liquids, Proc. Camb. Phil. Soc., vol. 16, p. 600, 1912.

[4] Max Margules, Uber die Bestimmung des Reibung und Gleitungs Coefficienten aus ebener Bewegungen einer Flussigkeit; Sitzungsber. Akad.-Wiss. Wein., vol. 83, pt. 2, p. 585, 1881.

4. TIMING EQUIPMENT

The time-measuring apparatus was a stop watch, reading to 0.2 second and started and stopped automatically by an electromagnet

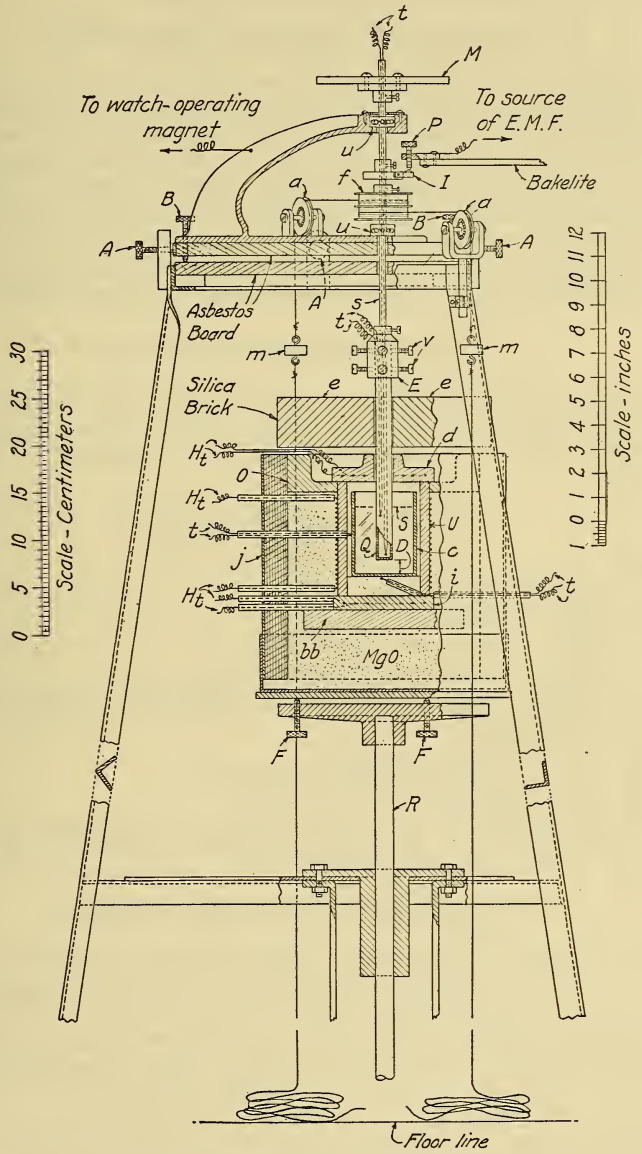

FIGURE 1.—*Lateral view of complete set-up.*

A and *B*, adjusting screws; *a*, pulley; *bb*, refractory; *c*, stationary cylinder or crucible; *D*, bottom clearance; *d*, inner cover; *E*, stirrer clamp; *e*, outer cover; *F*, leveling screws; *f*, drum; H_t leads to heating elements; *I*, rotating mercury contact; *i*, bottom heating plate; *j*, metal jacket; *M*, metal disk; *m*, driving masses; *O*, refractory; P, stationary contact; *Q*, rotating cylinder or stirrer; *R*, supporting shaft for furnace; *S*, glass surface; *s*, stirrer shaft; *t*, thermocouple leads; *U*, lateral heating unit; *u*, ball bearings; *v*, adjusting screws.

operated through the secondary of a telegraph relay. There were two breaks in the primary circuit of this relay. The tip of the sta-

tionary screw P and the mercury in an overfull iron trough I, mounted on the shaft (s), constituted the terminals of one break; the other, a knife switch, was operated manually. It was possible to measure the time required for from 1 to 8 complete revolutions.

5. TEMPERATURE MEASURING EQUIPMENT

The temperature-measuring equipment consisted of four platinum to platinum-rhodium thermocouples, a potentiometer and a cold-junction box of known and constant temperature. The hot junctions of two couples were placed inside of the stirrer, one at the bottom and the other at about the level of the upper surface of the molten glass. After placing these the stirrer was filled at least half full with pulverized corundum to prevent convection currents of air from reaching the hot junctions. The hot junctions of the other two couples were placed at the side and bottom, respectively, of the crucible, on the outside.

IV. EQUATION FOR VISCOSITY

The theoretical relation [5] for an ideal apparatus of the two coaxial cylinder type, having the liquid between them, when expanded to meet the conditions of test for this investigation becomes

$$\text{Viscosity, } \eta = \frac{30Wgr(d_2^2 - d_1^2)}{\pi^2(h+k)Nd_2^2d_1^2} \tag{1}$$

in which

η = viscosity in poises.
W = effective load.
g = the acceleration of gravity.
r = radius of drum + radius of cord.
h = wetted height, or depth of immersion of the stirrer in the glass.
N = revolutions per minute.
d_1 = outer diameter of the stirrer.
d_2 = inner diameter of the crucible.
k = "end effect" (a constant which is a function of d_1, and the "bottom clearance" D).

V. EVALUATION OF CORRECTIONS

Before making the necessary adjustments to attain constant speed, to determine the machine friction, or to make actual viscosity tests, it was necessary to aline pulleys (a, a) in such positions that (1) the plane of rotation of each pulley was truly vertical and contained the point of contact of the drum and the cord extending from the pulley to the drum; (2) the point of contact of the pulley and the cord was between the two horizontal planes enclosing that portion of the drum on which this cord was wound; and (3) the pulleys, placed on opposite sides of the drive shaft, were so located that their centers and the axis of this shaft were in a common vertical plane.

[5] E. W. Washburn, Univ. of Ill. Eng. Exp. Sta. Bull. 140, p. 12, April 1924.

1. THE ATTAINMENT OF CONSTANT SPEED

The device of the familiar Atwood machine was used in order to insure, during each test, a uniform speed (N) at which the resisting torque offered by the material under test just equalled that maintained by the effective load W. A rider, placed initially on one of the weights, M (fig. 1) was removed automatically at a time, determined by trial, such that the total remaining effective load was just able to maintain against the resisting torque of the viscous material under test, the velocity attained at the instant of removal of the rider. The proper point at which this rider should be removed was considered to have been determined when, following its removal at that point, the times required for the last 6 and for the last 8 revolutions were found to be in the ratio 6:8 (table 1). The attainment of this constancy of speed is essential since the computed value of viscosity is in each case directly proportional to the time required per revolution.

TABLE 1.—*Errors resulting from inconstancy in r.p.m.*

Trial no.	Rider travel	Time required for last—		$\frac{T_6}{T_8}$	Estimated time, T_6, at constant r.p.m.	Estimated residual error due to acceleration
		6 revs. T_6	8 revs. T_8			
	cm	*Sec.*	*Sec.*		*Sec.*	*Percent*
1a	1.0	8.2	11.2	0.732	----------	5.2
1b	1.2	8.0	11.1	.731	----------	2.6
1c	1.4	8.0	10.9	.734	----------	2.6
1d	1.6	8.0	10.8	.741	----------	2.6
1e	2.0	7.8	10.4	.750	7.8	0.0
2a	.5	18.3	23.7	.771	----------	20.0
2b	.3	18.6	24.6	.756	----------	8.4
2c	.2	18.75	25.1	.747	----------	1.3
2d	.2+	18.73+	25.0	.749	18.70	.18

2. FRICTION CORRECTIONS

The machine friction, F, will vary, depending on the total load applied to the system. Obviously F could not be determined under conditions of actual test, for loads such as would be required to rotate the stirrer, because the resisting torque produced by the glass alone was not known. Therefore, it was necessary to use the empty viscometer and the set-up A shown in figure 2 rather than set-up B which was used in the actual tests of viscosity.

After the bearings had been adjusted determinations were made, for various values of L (fig. 2, A), of the corresponding values of the load difference, a', required to maintain in each case a uniform rate of rotation.[6] It was found that, for a given value of L, the friction $2(L+a)$ in set-up B was less than a'. The amount of this was determined and assumed to be true for all loads used in actual tests. Later in the investigation, when the bearings were recleaned and reset, new values were determined.

[6] At speeds in excess of 30 r.p.m. there was a slight variation from the linear relation between F and L.

3. EVALUATION OF "END EFFECT"

The "end effect", k, may be defined as a factor proportional to the resisting torque produced by the viscous material under test acting on the end of the stirrer. In order to evaluate k it was necessary to use a liquid of known viscosity. Accordingly a "simple viscous" petroleum oil (that is, obeying Poiseuille's law) and known as "Sunoco Golden", was chosen because, in the convenient temperature range 5° to 30° C., it had viscosity values of the same order of magnitude as those of molten glasses. Its viscosity-temperature relation could be expressed by the equation:[7]

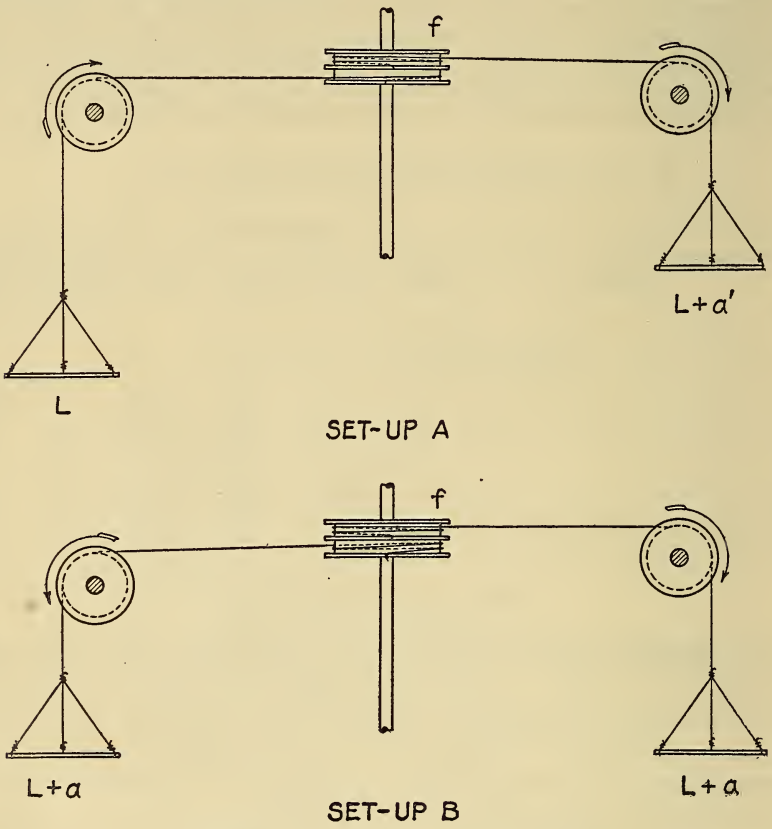

FIGURE 2.—*Diagrams of driving system.*

Set-up A shows arrangement for determining friction corrections for various loads and set-up B shows arrangement used in viscosity tests. a' effective driving weight, set-up A; $2(L+a)$; driving weight, set-up B; f, drum.

$$(\mathrm{Log}_{10}\eta - A)\ (T - B) = C \qquad (2)$$

in which

$A = -4.6392.$
$B = -71.3375.$
$C = 701.6.$
$T =$ temperature in °C.
$\eta =$ viscosity in poises.

When making determinations of k, the furnace (fig. 1) was replaced by a water bath, and the crucible by a glass cylinder whose dimen-

[7] Herschel, W. H., Viscosity and Temperature Changes, Oil and Gas J., vol. 25, p. 146, Dec. 2, 1926.

sions, except height, were approximately those of the refractory crucibles. Similarly, the refractory stirrer was replaced by a glass replica. The temperature of the oil in the glass cylinder was controlled by the water bath. In setting up the viscometer the stirrer was adjusted by means of screws, v (fig. 1), so as to rotate about its own axis, and that axis brought to a position vertical and concentric with the crucible. The clearance, D, at room temperature, between the end of the stirrer and the bottom of the crucible was then determined to ± 0.05 cm, which variation would not produce errors greater than 0.5 percent in computed values of viscosity.

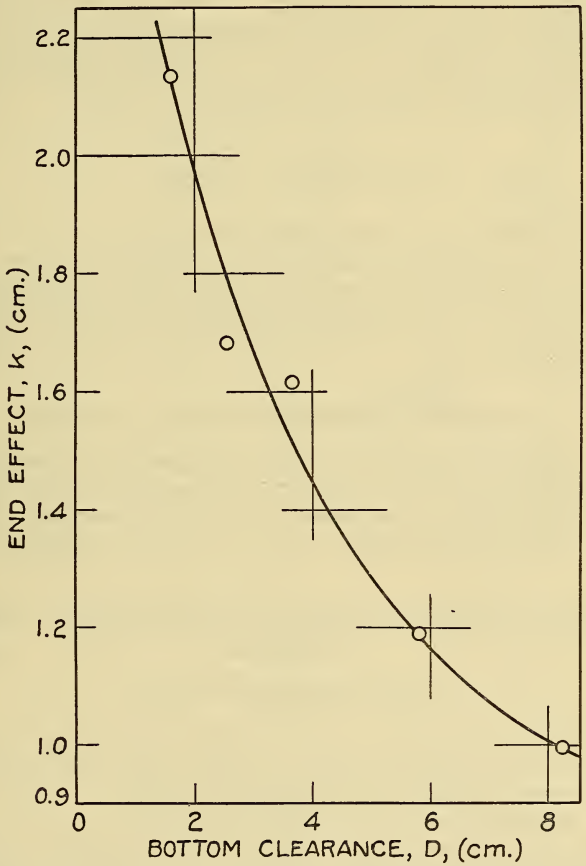

FIGURE 3.—*Showing "end effect" k as a function of bottom clearance D.*

From a consideration of the definition of unit viscosity and of equation (1) for viscosity, η, it can be shown that k is a function of d_1, d_2, and the bottom clearance D, but it cannot be thus shown whether k is or is not a function of h, N, or η. Although it had been shown previously by Proctor and Douglas [8] that k is not a function of h, N, or η, a number of tests were made, the results of which appear to be in accord with their conclusions. Therefore, since in any

[8] Proctor, R. F., and Douglas, R. W., Measurement of the Viscosity of Glass at High Temperatures by the Rotating Cylinger Viscometer, Proc. Phys. Soc. (Br.), vol. 41, pt. 5, no. 230, Aug. 15, 1929.

given test, d_1 and d_2 were also constant, the bottom clearance D remains as the only variable of which k may be a function. The form of this function was found by determining values of k corresponding to various values of D by substitution in equation (1), η being known from equation (2). These values of k were plotted (fig. 3) against the corresponding values of D, the best curve drawn through the points, and its equation determined as:

$$k = \frac{6.3}{(D+2.4)^{0.8}} \tag{3}$$

Theoretically, k is a function of d_1. Therefore, since the diameters of the refractory stirrers used in viscosity determinations differed slightly from the diameter (1.8 cm) of the calibrating glass stirrer, a modification of equation (3) was used, this modification being based on the work of Lillie.[9] Equation (3) then becomes:

$$k = \frac{6.3}{(D+2.4)^{0.8}} \cdot \left(\frac{d_1}{1.8}\right)^{1.18} \tag{4}$$

where d_1 is the diameter of the refractory stirrer.

It was found that closer duplication in results could be secured by stirring the oil immediately preceding the taking of readings, though this had the effect of increasing the apparent viscosity. Accordingly all determinations were immediately preceded by 20 turns of the stirrer at about 50 r.p.m.

4. RELATION OF EFFECTIVE LOAD TO R.P.M.

If glass, in the temperature range considered, is a "simple viscous" liquid, the values of W plotted against corresponding values of N should lie in a straight line passing through the origin. Any results which did not plot reasonably close to such a straight line were discarded.

VI. METHOD OF PROCEDURE FOR MEASURING VISCOSITY OF GLASS

1. ADJUSTMENT OF SET-UP

Preliminary to the actual viscosity tests, specimens of glass were molded in a form approximating the form assumed by the molten glass in the crucible and with the stirrer in place.

Having fastened a stirrer in the clamp E (fig. 1), the set-up was adjusted so that the stirrer was vertical, rotated about its own axis, and was concentric with the crucible. The furnace could then be lowered, the glass specimen inserted in the crucible, and again raised until the stirrer was in the preformed depression in the glass and in the same relative position occupied during a test. The top covers d and e (fig. 1) could then be put in place and the temperature raised to the temperature at which the glass was to be tested. In making a test it was necessary to determine the bottom clearance D and the "wettedheight" h, and to so adjust the apparatus that constant speed during a test would be assured.

[9] Lillie, H. R., Margules' Method of Measuring Viscosity Modified to Give Absolute Values, Phys. Rev., vol. 8, pp. 347 to 362, July 15, 1930.

2. DETERMINATION OF BOTTOM CLEARNACE *D* AND "WETTED HEIGHT" *h*

The bottom clearance *D* was checked occasionally by raising the furnace, while holding the temperature constant and with the molten glass in the crucible, until the bottom of the crucible just touched the stirrer. The furnace was then lowered a measured distance which determined the clearance *D*.

From figure 4 it is apparent that the wetted height, *h*, is equal to the total exposed length of the stirrer (*H*) minus the distance $L'+b$. This distance was determined by one of the following two methods.

At temperatures of 1,100° C. or above glass is a fairly good electrical conductor and this permitted the use of a gage (of cold length *L*) composed of two parallel platinum wires in series with a source of emf and a potential indicator. The gage was mounted on the viscometer stand so as to be vertically adjustable by means of a rack and pinion. After removing one of the furnace cover bricks (*e*, fig. 1) the gage was lowered through a hole in the cover, *d* (fig. 1), and the instant of contact of the lower ends of the wires with the glass was made evident by the indicator. The value of "*b*" (fig. 4) was determined by means of an "inside" caliper.

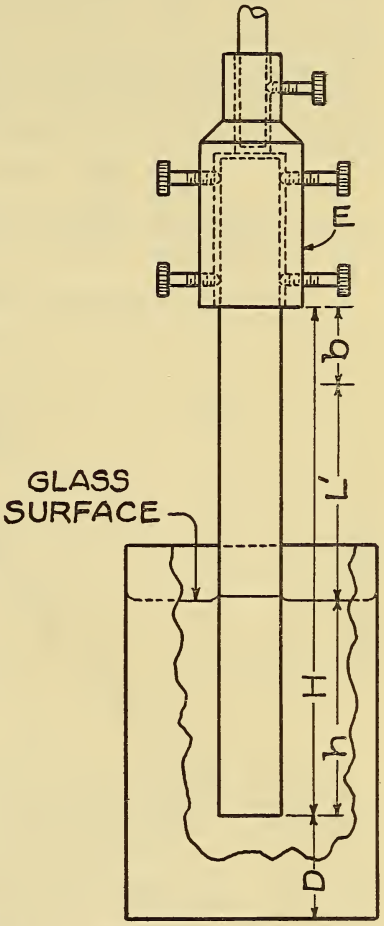

FIGURE 4.—*Sketch showing dimensions involved in determining "wetted height" h.*

For temperatures below 1,100° C. a gage was made of a refractory tube attached to a hollow metal holder supporting it vertically from its upper end. The lower end of this gage was left open while the upper end was connected to a vacuum pump by means of a small copper tube. An ordinary glass U-tube manometer of the closed end type was connected to the line between the gage and pump. This gage also was adjusted vertically with the rack and pinion. With the pump in operation the gage was lowered until the manometer indicated contact of the lower end of the gage with the surface of the molten glass, when the distance *b* was measured.

Consistent values for $L'+b$ were difficult to obtain in spite of the most painstaking precautions. However, in 135 viscosity determinations, during the course of each of which from 2 to 4 measurements of $L'+b$ were made, the extreme variation was 0.13 cm, while the mean of all variations was 0.03 cm, or approximately 0.7 percent.

This would produce a corresponding mean error in the computed value of the viscosity of less than 0.5 percent.

In determining the wetted height it was necessary to take into consideration the increase in length of the stirrer, as well as of the two gages, caused by their thermal expansion when exposed to the furnace temperatures. The coefficients of thermal expansion of the stirrer, and of the wire or refractory of the two gages, was fairly definitely known. Nevertheless, the temperature gradients in the stirrers and gages not being known, certain tacit assumptions were necessary when calculating their lengths under test conditions. Unless changes in lengths of the gages and stirrer are taken into account, errors as large as 2.0 percent may be introduced into the computed value of viscosity.

VII. GLASSES STUDIED

The approximate chemical compositions and indices of refraction of the glasses whose viscosities were measured are given in table 2.

TABLE 2.—*Approximate compositions of the glasses tested*

Oxide	Kind of glass					
	Light barium crown	Light crown (soda-lime)	Boro-silicate crown	Dense flint	Medium flint	Barium flint
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
SiO_2	47.5	74	65	41.0	45.5	45.5
Na_2O		12.5	8	.5	3.0	
K_2O	8.5	.2	12.5	6.5	5.0	8.0
B_2O_3	4.0		11.5			
ZnO	9.5		2.5			8.0
BaO	30.5		0.5			15.0
CaO		13.5				
PbO				52.0	46.5	23.5
Index of refraction	1.574	1.524	1.517	1.650	1.620	1.605

VIII. RESULTS

Values of viscosity were computed for any one glass from the results of all apparently satisfactory tests made on that glass. The logarithms of these values were plotted against the corresponding temperatures and the best possible initial graph was drawn through the plots. The mean percentage deviation of all computed values from the corresponding values shown by the initial graph was then determined. Following this a final graph was drawn (of which fig. 5 is an example) disregarding all those values whose percentage deviation was greater than four times the mean deviation.[10] Viscosity values for the glasses, tested at 900°, 1,000°, 1,100°, 1,200°, 1,300°, and 1,400° C. are given in table 3. In table 4 are given the equations (and the values of the constants involved), expressing these viscosity-temperature relations. These equations, except for borosilicate crown, are based on results obtained with crucibles and stirrers of porcelain designated as *A*.

[10] Goodwin, H. M., Precision Measurements and Graphical Methods, p. 21, McGraw-Hill Book Co.

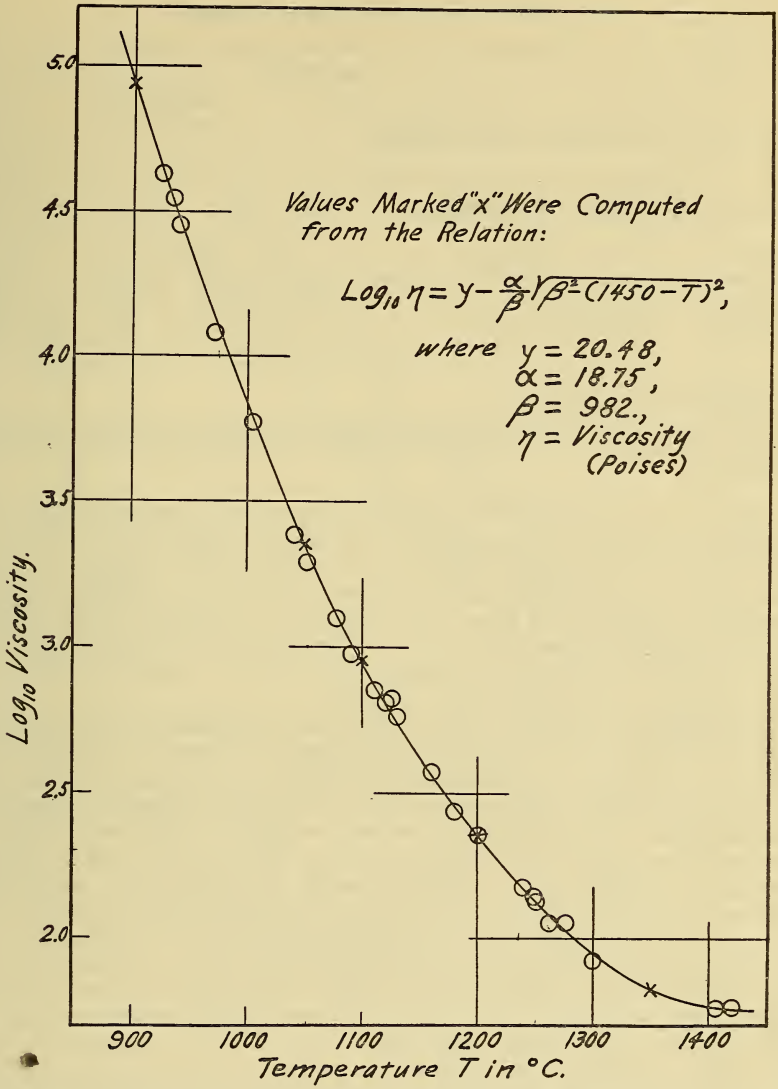

FIGURE 5.—*Showing log* $_{10}$ *of viscosity as a function of temperature in °C. for light barium crown glass.*

TABLE 3.—*Numbers of samples and determinations, and résumé of most probable viscosity values*

Kind of glass	Number of samples	Number of determinations	Viscosity at—					
			900°C.	1,000°C.	1,100°C.	1,200°C.	1,300°C.	1,400°C.
			Poises	*Poises*	*Poises*	*Poises*	*Poises*	*Poises*
Light barium crown	25	160	90,000±2,500	6,600±200	870±35	225±7	87±3	57±1
Light crown (soda-lime)	7	20	148,000±3,000	20,200±800	3,730±200	1,030±50	360±20	151±4
Borosilicate crown	6	30	----------	(See table 5)				
Dense flint	7	21	6,600±200	1,525±35	460±25	186±6	88±3	47±1
Medium flint	2	9	----------	2,040±90	580±20	216±6	105±3	65±4
Barium flint	3	15	----------	8,000±275	1,500±50	385±15	140±5	76±2

TABLE 4.—*Viscosity-temperature relations*

[General equations expressing the viscosity-temperature relations of the glasses studied]

Kind of glass	Viscosity temperature relation [1]	Values of constants				
		α	β	γ	δ	ϵ
Light barium crown	$\text{Log}_{10}\eta=\gamma-\frac{\alpha}{\beta}\sqrt{\beta^2-(1{,}450-T)^2}$	18.75	982.	20.48		
Soda-lime	$\text{Log}_{10}\eta=\frac{\beta}{(T+273.1)^2}-\alpha$	.727	8.13×10^6			
Borosilicate crown[2]	$\text{Log}_{10}\eta=\alpha+\beta(29-0.02T)+(29-0.02T)^2$	1.172	75.204	5.79		0.002
Dense flint	$\text{Log}_{10}\eta=\alpha+\beta\gamma^{-\epsilon T}$	.648	24.42	3.073		.002
Medium flint	$\text{Log}_{10}(\text{Log}_{10}\eta-\delta)=\alpha-\beta\gamma^{-\epsilon T}$	.9115	.0775	.3375	1.614	.002
Barium flint	$\text{Log}_{10}\eta=\alpha+\beta(\gamma-\epsilon T)^{\delta}$	1.75	1.77	3.1	2.14	.002

η = absolute viscosity in poises.
T=temperature in the Centigrade scale.

[2] Equation based on results obtained with crucible and stirrer of platinum and before heating to higher temperatures. Equation does not fit where T=1,400°, probably because there was a marked increase in voltatilization.

Early in the investigation it became apparent that selective volatilization of certain components of the glasses might alter the compositions of the glasses sufficiently to affect their viscosities, but there were no practical means of preventing it. Solution of the crucible by the molten glass was found to be another factor which could alter the composition as a test proceeds. Visible evidence of attack on the crucibles and stirrers was especially pronounced in the case of tests on borosilicate crown glass.

Accordingly a limited number of tests were made on borosilicate crown glass using (1) a porcelain of different composition and denser structure (designated as porcelain *B*); and (2) platinum coverings for those surfaces of crucible and stirrer otherwise exposed to contact with the glass. The effects on viscosity values and chemical composition are summarized in tables 5 and 6. The irregular and widely divergent viscosity values obtained with porcelain *A* as compared with those obtained with porcelain *B* and with the platinum protected containers, when considered in connection with the changes in composition, are believed to be sufficient evidence that crucible solution may introduce large errors. It is believed that the change in composition of glass sample no. 3 (table 6) tested in platinum was caused by selective volatilization, and that this, in turn, resulted in the increased viscosity of this glass as shown by the curves in figure 6.

It is regretted that time did not permit testing all of the glasses in platinum, or even in porcelain *B*, which would apparently have been a decided improvement over porcelain *A*, although (as stated previously) there was much more solution of porcelain by the borosilicate crown than by any of the other glasses. Therefore, when considering the values in tables 3, 5, and 6, it should be remembered that they apply to glasses the compositions of which, at the actual time of test, are not accurately known.

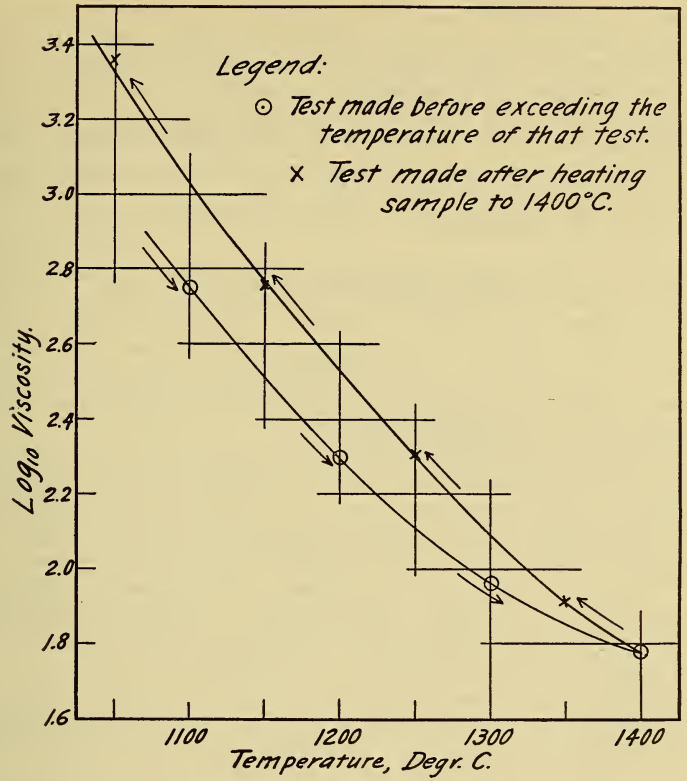

FIGURE 6.—*Showing change in viscosity of borosilicate crown glass (tested in platinum) due to volatilization.*

TABLE 5.—*Viscosity values*[1] *(poises), of borosilicate crown glass as measured in various crucibles*

Crucibles used	Number of samples	Number of determinations	Temperatures, ° C.				
			1,000	1,100	1,200	1,300	1,400
			Poises	*Poises*	*Poises*	*Poises*	*Poises*
Porcelain A	3	10	2,720±175	565±47	199±10	119±3	110±3
Platinum	1	10	[2] 2,000±10	560±11	200±6	90±2	60±1
Porcelain B	2	10	2,170±175	560±25	190±5	86±2	51±1

[1] Each of the above values of viscosity was determined before the sample was heated to higher temperatures.

[2] Value determined by extrapolation of log viscosity-temperature graph.

TABLE 6.—*Chemical analyses of variously treated borosilicate crown glasses*

Number of sample	Melt No.	Treatment	Analyses		
			SiO_2	R_2O_2	R_2O
			Percent	*Percent*	*Percent*
1 "control"	697	From molded sample [1] (before test)	65.8	0.3	19.6
2	668	After being held at 1,400° C. for 6 hours in crucible *A*	63.6	6.9	16.4
3	697	After being held at 1,400° C. for 9 hours in platinum crucible.	68.6	.4	18.0
4	697	After being held at 1,400° C. for 5 hours in crucible *B*	66.8	.6	18.6

[1] See pt. VI, 1, p. 72.

Changes in composition due to solution of crucibles and stirrers might be minimized by using porcelain of greater resistivity, or perhaps eliminated by using platinum containers and stirrers. This is not true of changes due to volatilization which could be avoided only by making the viscosity measurements under controlled conditions in which the sample could be kept in an atmosphere already saturated with the vapors of the volatile components of the glass under test.

IX. SUMMARY AND CONCLUSIONS

This paper reports an investigation of viscosities, at elevated temperatures, of six optical glasses—light barium crown; borosilicate crown; soda-lime; and dense, medium, and barium flint. Searle's modification of Margules' concentric cylinder type viscometer was adopted. The paper contains a description of the furnace, crucible and stirrers, driving mechanism, and timing and temperature-measuring equipment of the complete set-up.

The classical equation for viscosity was modified to adapt it to the apparatus. A fairly detailed description is given of the evaluation of certain factors and corrections such as production of constant speed, friction, "end effect", and relation of effective load to r.p.m., which evaluations it was necessary to establish prior to actual tests on the glasses. Further carefully made adjustments and measurements, such as the determination of the "wetted height" or depth of immersion of the stirrer in the glass, are necessary after the glass has been introduced into the apparatus and raised to the temperature of test.

The results of 255 viscosity tests on a total of 50 samples of the 6 optical glasses are summarized in equations expressing the mathematical relations of viscosity to temperature. Because of volatilization, as well as partial solution of crucibles and stirrers by the several glasses, especially borosilicate crown, the exact compositions of the glasses at the time of test are not known. An approximation of the importance of volatilization and solution as factors in viscosity determinations was obtained by a number of tests of the borosilicate crown glass in a crucible of special and more resistant porcelain, as well as with crucible and stirrer protected with platinum.

As a result of the investigation of the many factors involved in making viscosity determinations at high temperatures with the concentric cylinder type viscometer, it is believed that the information obtained enables the investigator to so evaluate and apply the necessary corrections as to make possible the obtaining of additional viscosity values of significant accuracy—insofar as the apparatus itself is concerned. It has been shown further that solution of crucible and stirrer by the glass, and volatilization of the glass, are factors of major importance because they may materially alter the composition of the glass during the course of a test. It should be a relatively simple matter to avoid contamination of the glass by solution of the container, but this is not true of changes due to volatilization. However, volatilization could conceivably be greatly minimized.

Washington, May 9, 1933.